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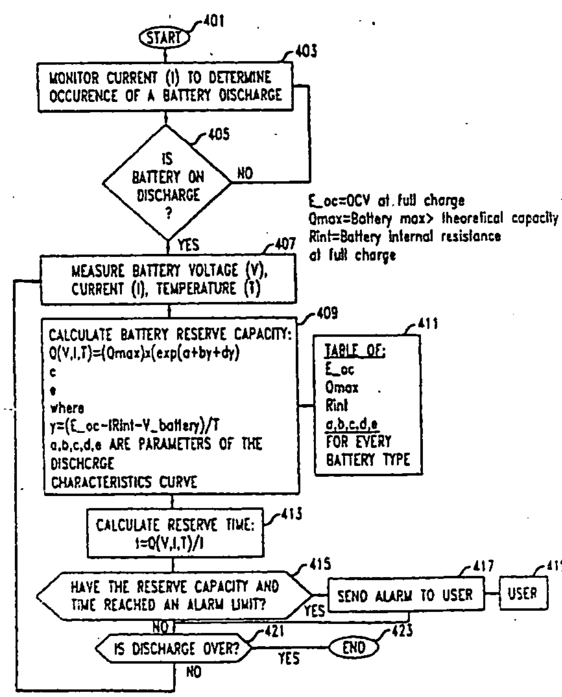
(54) Method and apparatus for predicting the remaining capacity and reserve time of a battery on discharge

(57) A highly accurate apparatus and method of predicting remaining capacity Q and reserve time t of a discharging battery to a selected end voltage is determined by an arrangement considering the open circuit voltage, battery voltage, battery temperature and its internal resistance. The remaining battery capacity Q is determined from the difference between the battery full charge open circuit voltage Eoc and the voltage loss due to the internal resistance of the battery IRint and the battery voltage on discharge divided by the battery temperature T, which is the temperature-corrected battery overvoltage.

FIG. 4



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Description

Field of the Invention

This invention relates to apparatus and a method of measuring and predicting the remaining capacity and reserve time of a discharging battery. It is particularly concerned with predicting the capacity and reserve time of flooded or sealed lead acid batteries during discharge to an end-voltage.

Background of the Invention

Predicting the remaining capacity and reserve time of a battery is important to the proper management of battery plants and of batteries remotely located. The fundamental method of prediction, of the prior art, is based on the Peukert equation:

$$t = aI^{b} \tag{1}$$

where t is the reserve time to a given end voltage, I is the discharge current and "a" and "b" are empirically determined parameters. The remaining reserve time during discharge is obtained by subtracting the actual time of discharge from the value "t" given by the equation. The only real time data used in this approach is the discharge current I, and the parameters "a" and "b" must be experimentally determined by extensive testing, data acquisition and parametric analysis. Once determined, these values are fixed and do not adapt to changing conditions and are not responsive to changing load requirements.

An attempt to be more responsive to changes in battery behavior during discharge is disclosed in the patent application Serial No. 08/013272, filed February 4, 1993, submitted by D. Levine et al which utilizes matrices of predetermined parameters which contain correlations for the slope of the voltage-versus-discharge time at various discharge currents, battery voltages during discharge and end voltages. The use of voltage-versus-time slopes for prediction allows the method to be highly adaptable to changes in battery behavior during discharge. This method requires extensive testing to derive the data to populate the matrices.

Another approach, disclosed by R. Biagetti and A. Pesco in U.S. Patent 4,952,862, operates by measuring the difference between battery voltage during discharges and the battery plateau voltage,

$$V_{battery} - V_p \tag{2}$$

During discharge this difference is plotted against a ratio of discharged capacity to the total discharge capacity available:

$$Q_{removed}/Q_{to\text{-}end\text{-}voltage} \tag{3}$$

This plot, created from measured data, is a single curve having an exponential and a linear region. This curve is used to determine remaining capacity and reserve time from the measured discharged capacity $Q_{removed}$ and the plateau voltage V_p. As in the above described method, extensive prior testing and data analysis of the particular battery being monitored is required and this method does not account for aging of the battery since measurement of the plateau voltage is a predetermined fixed value.

Another approach to determining the reserve time of a discharging battery, disclosed in US patent 4,876,513, takes advantage of the fact that when battery voltages (corrected for internal resistance) are plotted versus a ratio of ampere hours remaining to ampere hours available to a certain discharge voltage all discharge curves fall on a single curve. The battery voltages corrected for IR are calculated using a battery internal resistance that is measured periodically during discharge.

None of the existing methods for evaluating the state of a discharging battery works accurately at all temperatures, requires only a minimal number of parameters and is independent of the battery type being monitored.

Summary of the Invention

Therefore according to the invention, a method and apparatus for predicting reserve capacity and reserve time of a battery on discharge, is provided as claimed in claims 1 and 11.

A highly accurate apparatus and method of predicting remaining capacity Q and reserve time t of a discharging battery to a selected end voltage is based on measurable battery parameters and does not require extensive pretesting of the battery. The battery reserve time t of a discharging battery is determined by an arrangement considering the discharge current, battery voltage, battery temperature and the battery's internal resistance. The remaining battery capacity Q is determined from the ratio between a maximum theoretical capacity Q_{max} and its present capacity Q. A term defined by a sum of the battery full charge open circuit voltage Eoc and the voltage loss due to the internal resistance of the battery IR_{int} and the battery voltage on discharge divided by the battery temperature T, is computed as the temperature-corrected battery overvoltage η.

$$\eta = \frac{E_{oc} - IR_{int} - V_{battery}}{T} \tag{4}$$

The characteristics of the battery discharge are reduced to a ratio of a single remaining battery capacity to maximum theoretical capacity:

$$\frac{Q}{Q_{max}} \tag{5}$$

This normalized battery capacity value is plotted versus the temperature-corrected battery overvoltage to produce a discharge characteristic curve that is invariant to discharge rates, temperatures, battery size, and aging effects and which is dependent only on the battery's internal design. This normalized battery capacity is related by fitting parameters to the value η by the re-

lation

$$\frac{Q}{Q_{max}} = \exp^{(a+b\eta^{c}+d\eta^{e})} \qquad (6)$$

to characterize the discharge characteristic and determine Q.

A reserve time t is calculated from the determined value using the relation

$$t=\frac{Q}{I} \qquad (7)$$

The characteristic curve and the dynamic variables are stored in a computer and processed continuously to provide a continuing real time prediction of the remaining capacity and reserve time t of the battery on discharge.

Brief Description of the Drawing

FIG. 1 is a block schematic of a battery plant and its monitoring system;
FIG. 2 is a graph of a typical battery discharge curve in terms of battery voltage versus ampere-hours removed;
FIG. 3 is a graph of a typical battery discharge curve in terms of charge ratio versus temperature-corrected battery overvoltage; and
FIG. 4 is a flow graph illustrating the method of determining the remaining capacity Q and reserve time t of a discharging battery.

Detailed Description

The battery plant and monitoring system shown in the FIG. 1 includes a plurality of battery cells 101-1 to 101-n all of which are connected in series connection to power a load 102. A rectifier 103 is connected to receive AC line power and provide a rectified charging voltage to recharge the string of battery cells 101-1 to 101-n. A battery monitoring unit 105 having stored program control is connected to a controller-battery interface 110. The battery interface 110 has connections 111-1 to 111-n to sense the voltage of each battery cell and a connection 112 to sense the load current and a connection 113 to sense a temperature of at least one battery cell. The battery monitoring unit has an access device 117 for user input and data output.

The battery monitoring unit 105 includes a stored program control which accepts data from the battery interface and background data from the user input/access device 117. The stored program controller also includes instructions for utilizing the data input for predicting a remaining charge capacity and reserve time until discharge to a specified end voltage of the batteries 101 in the string of batteries. This determination is communicated through the user access interface 117 to a data output which may include communication with a distant output device.

The conventional graph of battery discharge capacity is shown by the graph illustrated in the FIG. 2. This discharge curve is plotted in terms of voltage versus ampere-hours. This curve exhibits three distinct characteristic regions. The initial region 201 shows an initial drop in battery voltage due to the phenomenon of activation and ohmic resistance. The second subsequent region 202, shows a gradual decrease in battery voltage due to a continuous increase in the internal resistance of the battery during discharge. This resistive increase is due to depletion of reactants and/or active surface areas in the battery. The final region 203 shows a sharp decrease in the battery voltage due to the discharge reactions becoming starved of reactants, whose transport to the electrode surfaces has become mass-transfer limited. These complex changes during discharge are believed to be related to the remaining capacity of the battery during discharge.

The discharge characteristic of a battery is based on a ratio of remaining capacity/ maximum theoretical capacity Q/Qmax versus the temperature corrected battery overvoltage. While the actual capacity Q may be used in place of Qmax, the ratio is invariant to battery size. The remaining capacity to an end voltage, at a given battery voltage, is calculated from the difference between the remaining capacity Q at that battery voltage and the remaining capacity at that end voltage.

The effect of temperature on discharge is shown in the graph of FIG. 3, which illustrates the discharge curves 301 and 302 of the same battery at two different temperatures.

The method of predicting the remaining capacity and reserve time t of a discharging battery according to the stored instructions of the controller is shown in the flow diagram of FIG 4. The process starts at terminal 401 and proceeds to the block 403 whose instructions have the controller retrieve the discharge current sensed by the interface monitor. The instructions, operate as per decision block 405, to determine if the battery is in discharge by observing the direction of current flow. If the battery is not discharging the controller continues to monitor current flow as per block 403. If the battery is in discharge, battery voltage, current and temperature are measured and recorded per the instructions of block 407. The instructions of block 409 use these monitored parameters to calculate a battery reserve capacity. The process uses a table of battery characteristics and parameters provided from memory as per block 411. The calculation process determines the remaining battery capacity per:

$$Q(V,I,T) = (Q_{max}) \times \exp(a + b\eta^{c} + d\eta^{e}) \qquad (8)$$

where the term η is:

$$\eta=\frac{(E_{oc} - IR_{int} - V_{battery})}{T} \qquad (9)$$

and a, b, c, d and e are curve fitting parameters of the discharge characteristic curve. The next step defined by the instruction of block 413 calculates the actual predicted reserve time t by the relation of:

$$t = Q(V,I,T)/I \qquad (10)$$

The subsequent instructions of decision block 415 determine if the calculated reserve capacity and time have reached an alarm limit. If an alarm limit is reached, the alarm is sent to the user as indicated in the block 417 and block 419. If no limit has been reached, the decision block 421 determines whether the discharge condition is over. If discharge has terminated, the process is terminated as per block 423. If the discharge is continuing, the flow returns to the Block 407 and the process is continued.

Claims

1. A method of predicting a remaining capacity and reserve time of a battery in a process of discharge, comprising the steps of:

   determining an open circuit voltage of the battery;
   CHARACTERIZED BY:
   measuring a discharge current and discharge voltage of the battery in the process of discharge;
   measuring a temperature of the battery in the process of discharge;
   determining a remaining reserve capacity of the battery in a process of discharge by deriving a value for battery overvoltage based on determined and measured battery parameters including the open circuit voltage, the discharge current, the discharge voltage and the temperature of the battery;
   using the reserve capacity to determine the reserve time remaining to a final end voltage.

2. A method of predicting a remaining capacity and reserve time of a battery in a process of discharge as claimed in claim 1:
   wherein the battery overvoltage definition is expressed as

$$\eta=\frac{E_{oc} - IR_{int} - V_{battery}}{T}.$$

3. A method of predicting a remaining capacity and reserve time of a battery in a process of discharge as claimed in claim 2 wherein the step of determining a remaining reserve capacity of the battery in a process of discharge includes expressing a ratio of remaining capacity to maximum capacity as an exponential function.

4. A method of predicting a remaining capacity and reserve time of a battery in a process of discharge as claimed in claim 3 wherein the exponential expression is given the form

$$\frac{Q}{Q_{max}} = e^{(a+b\eta^{c}+d\eta^{e})}$$

   where Q_{max}, a, b, c, d, and e are predetermined parameters determined by the battery embodiment;

5. A method of predicting a remaining capacity and reserve time of a battery in a process of discharge as claimed in claim 1 wherein the step of using the reserve capacity to determine the reserve time remaining to a final end voltage includes a step of measuring a discharge current and a ratio of the reserve capacity to the discharge current.

6. A method of predicting the reserve time of a discharging battery with a known maximum capacity, comprising the steps of:

   determining temperature dependence of a battery overvoltage of the discharging battery;
   reducing the temperature dependence of a battery overvoltage to a ratio of battery capacity of the discharging battery to its maximum capacity; and
   measuring the discharge current and combining it with the battery capacity of the discharging battery to determine a reserve time to discharge the battery to an end voltage.

7. A method of predicting the reserve time of a discharging battery with a known maximum capacity as claimed in claim 5, wherein the step of reducing the temperature dependence of a battery overvoltage to a ratio of battery capacity of the discharging battery to its maximum capacity includes evaluation of the equation,

$$\frac{Q}{Q_{max}} = e^{(a+b\eta^{c}+d\eta^{e})}.$$

8. A method of predicting the reserve time of a discharging battery with a known maximum capacity as claimed in claim 5, wherein the step of determining temperature dependence includes evaluation of the equation,

$$\eta = \frac{E_{oc} - IR_{int} - V_{battery}}{T}.$$

9. A method of predicting the remaining capacity and reserve time of a discharged battery, characterized by the steps of:

   measuring a discharge voltage of the battery, measuring the discharge current of the battery and measuring the temperature of the battery to determine a temperature corrected battery overvoltage η of the form:

$$\eta = \frac{E_{oc} - IR_{int} - V_{battery}}{T}$$

where E_{oc} is the battery open circuit voltage, I is the discharge current of the battery, R_{int} is the internal resistance of the battery, $V_{battery}$ is the battery voltage during discharge and T is the battery temperature;

determining the value Q for the remaining capacity using a characteristic curve of the form:

$$\frac{Q}{Q_{max}} = e^{(a+b\eta^{c}+d\eta^{e})}$$

and using predetermined values for the parameters Q_{max}, a, b, c, d, and e;

and determining the reserve time according to the relation:

$$\text{Reserve Time} = \frac{Q}{I}.$$

10. A method of predicting the remaining capacity and reserve time of a discharging battery, characterized by the steps of:

measuring discharge data of the battery at selected constant discharge currents to derive a battery capacity versus temperature corrected battery overvoltage characteristic curve according to the following relation:

$$\frac{Q}{Q_{max}} = e^{(a+b\eta^{c}+d\eta^{e})}$$

where:

$$\eta = \frac{E_{oc} - IR_{int} - V_{battery}}{T}$$

Q_{max} is maximum theoretical capacity of the battery, E_{oc} is the battery open circuit voltage, I is the discharge current of the battery, R_{int} is the internal resistance of the battery, $V_{battery}$ is the battery voltage during discharge, T is the battery temperature, and a, b, c, d, and e are curve fitting parameters related to the design of the battery; and solving for the remaining capacity value of reserve time t according to the relation;

$$t = \frac{Q}{I}$$

11. Apparatus for predicting a reserve capacity and remaining reserve time of a battery in discharge; comprising:

CHARACTERIZED BY:

voltage sensing circuitry connected to a terminal voltage of the battery;

current sensing circuitry connected for sensing a load current of the battery;

a temperature sensing device positioned for sensing a temperature of the battery;

a battery monitoring circuit connected to receive input from the voltage sensing circuitry, the current sensing circuitry and the temperature sensing device; and including a reserve time prediction sub-unit having:

a stored program controller for controlling and receiving input from the voltage sensing circuitry, the current sensing circuitry and the temperature sensing device and determining if the battery is discharging,

memory associated with the stored program controller and including battery characteristic data including E_{oc},R_{int},Q_{max}, and battery parameters;

the stored program controller including instructions for determining a value of:

$$\frac{Q}{Q_{max}} = e^{(a+b\eta^{c}+d\eta^{e})}$$

and calculating a predicted reserve time t using the equation by the relation:

$$t = \frac{Q}{I}.$$

12. A method of predicting a remaining capacity and reserve time of a battery in a process of discharge, comprising the steps of:

determining an open circuit voltage of the battery;

CHARACTERIZED BY:

measuring a discharge current and discharge voltage of the battery in the process of discharge;

using a temperature of the battery environment in the process of discharge;

determining a remaining reserve capacity of the battery in a process of discharge by deriving a value for battery overvoltage based on determined and measured battery parameters including the open circuit voltage, the discharge current, the discharge voltage and the temperature of the battery;

using the reserve capacity to determine the reserve time remaining to a final end voltage.

13. A method of predicting a remaining capacity and reserve time of a battery in a process of discharge as claimed in claim 11:

wherein the temperature related battery overvoltage definition is expressed as

$$\eta T = E_{oc} - IR_{int} - V_{battery}$$

where T is battery related temperature, E_{oc} is the open circuit voltage of the battery, IR_{int} is an internal

battery voltage, and $V_{battery}$ is the discharge battery voltage.

14. A method of predicting a remaining capacity and reserve time of a battery in a process of discharge as claimed in claim 12 wherein the step of determining a remaining reserve capacity of the battery in a process of discharge includes expressing a ratio of remaining capacity to maximum capacity as a function of η where

$$\frac{Q}{Q_{max}}=f(\eta)$$

where Q_{max}, is a predetermined parameter of the battery embodiment.

15. A method of predicting a remaining capacity and reserve time of a battery in a process of discharge as claimed in claim 13 wherein the expression is given the form

$$\frac{Q}{Q_{max}}=e^{(a+b\eta^{c}+d\eta^{e})}$$

16. A method of predicting a remaining capacity and reserve time of a battery in a process of discharge, comprising the steps of:

determining an open circuit voltage of the battery;
CHARACTERIZED BY:
measuring a discharge current and discharge voltage of the battery in the process of discharge;
determining a remaining reserve capacity of the battery in a process of discharge by deriving a value for battery overvoltage based on determined and measured battery parameters including the open circuit voltage, the discharge current, and the discharge voltage of the battery;
using the reserve capacity to determine the reserve time remaining

17. A method of predicting a remaining capacity and reserve time of a battery in a process of discharge as claimed in claim 15:

including further measuring a temperature of the battery in the process of discharge.

18. A method of predicting a remaining capacity and reserve time of a battery in a process of discharge as claimed in claim 15:

including further considering that the battery is operating at ambient temperature and utilizing that temperature.

FIG. 1

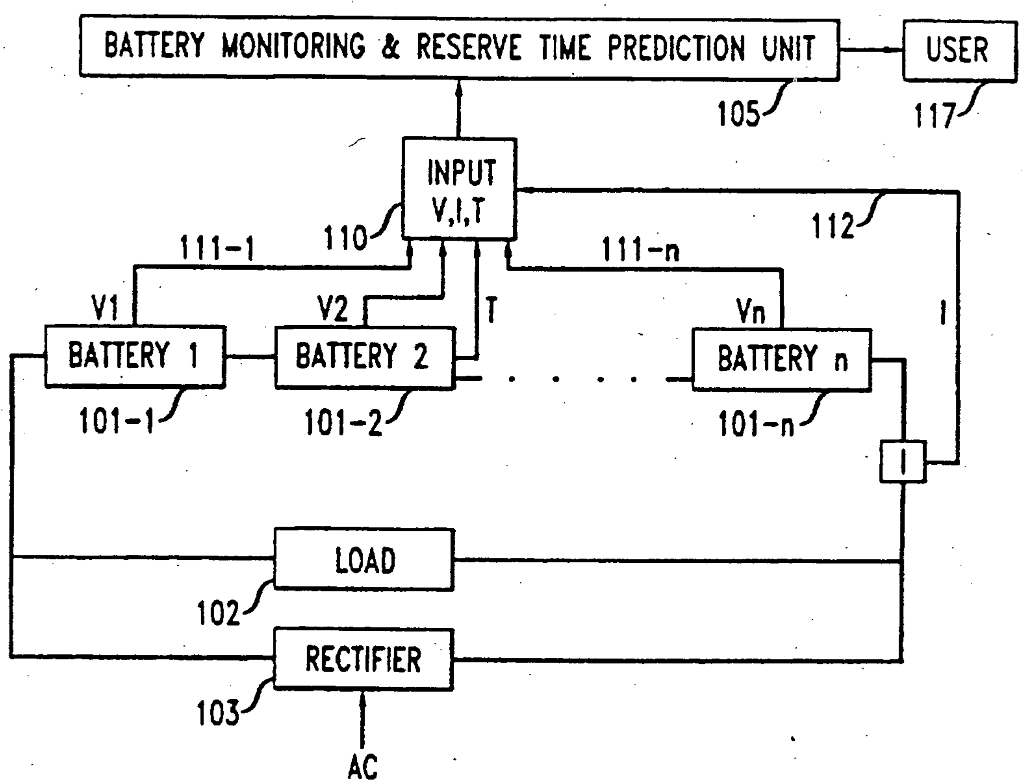
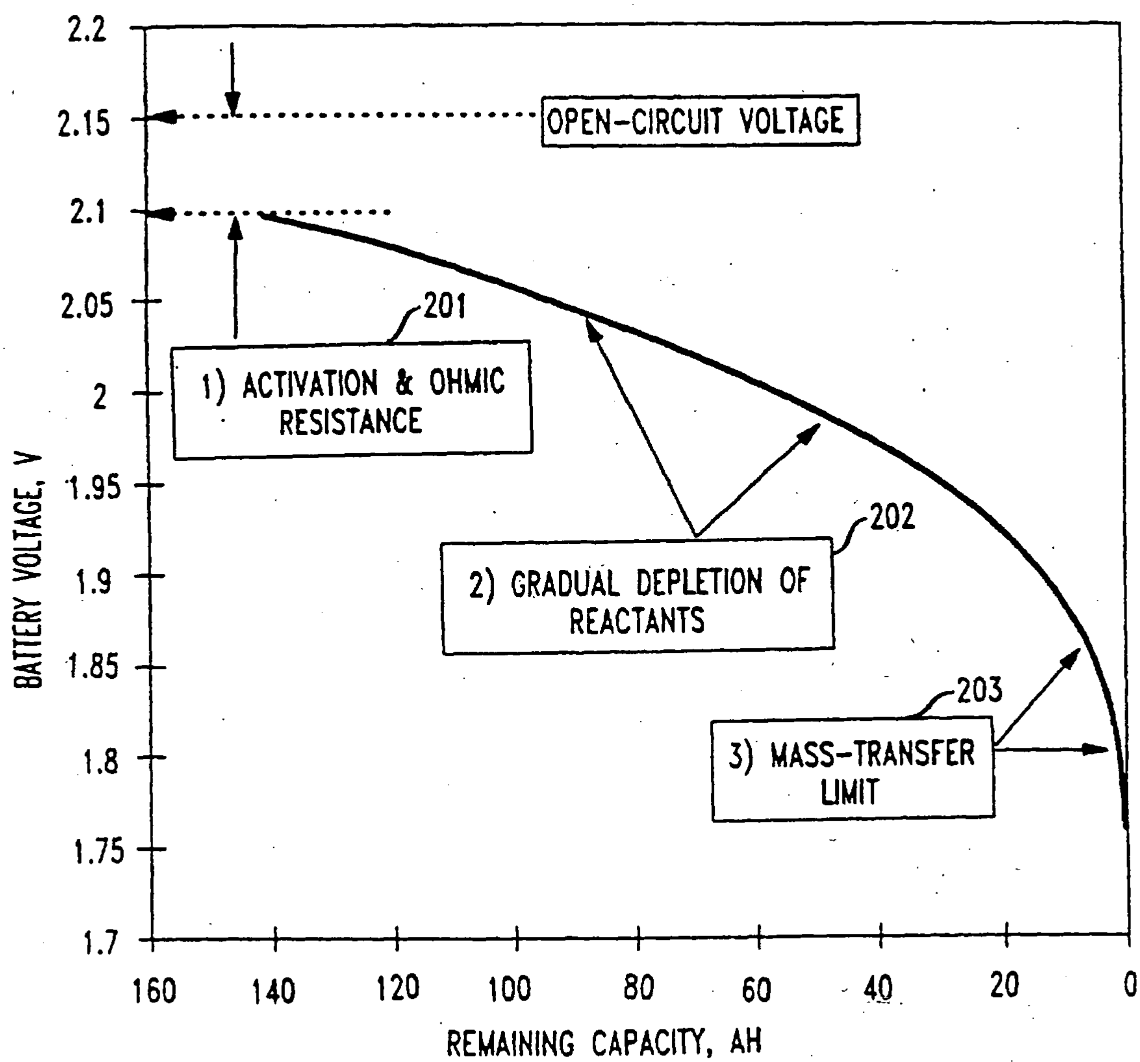

BATTERY MONITORING & RESERVE TIME PREDICTION UNIT
USER
105
117
INPUT
V,I,T
110
112
111-1
111-n
V1
V2
T
Vn
I
BATTERY 1
BATTERY 2
BATTERY n
101-1
101-2
101-n
I
LOAD
102
RECTIFIER
103
AC

FIG. 2



2.2
2.15
2.1
2.05
2
1.95
1.9
1.85
1.8
1.75
1.7
BATTERY VOLTAGE, V
OPEN-CIRCUIT VOLTAGE
201
1) ACTIVATION & OHMIC RESISTANCE
202
2) GRADUAL DEPLETION OF REACTANTS
203
3) MASS-TRANSFER LIMIT
160
140
120
100
80
60
40
20
0
REMAINING CAPACITY, AH

FIG. 3

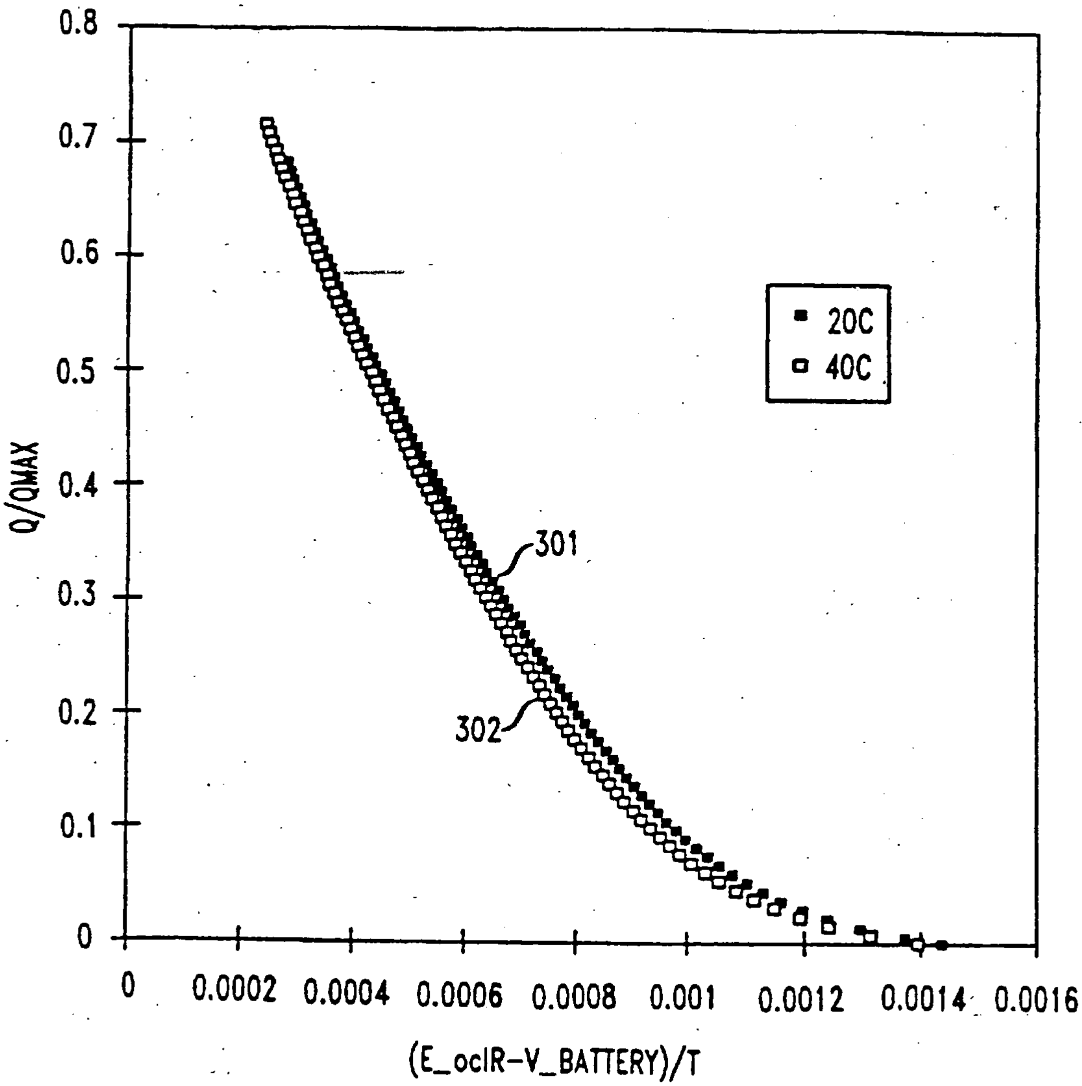

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Q/QMAX
20C
40C
301
302
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
0.0014
0.0016
(E_ocIR-V_BATTERY)/T

FIG. 4

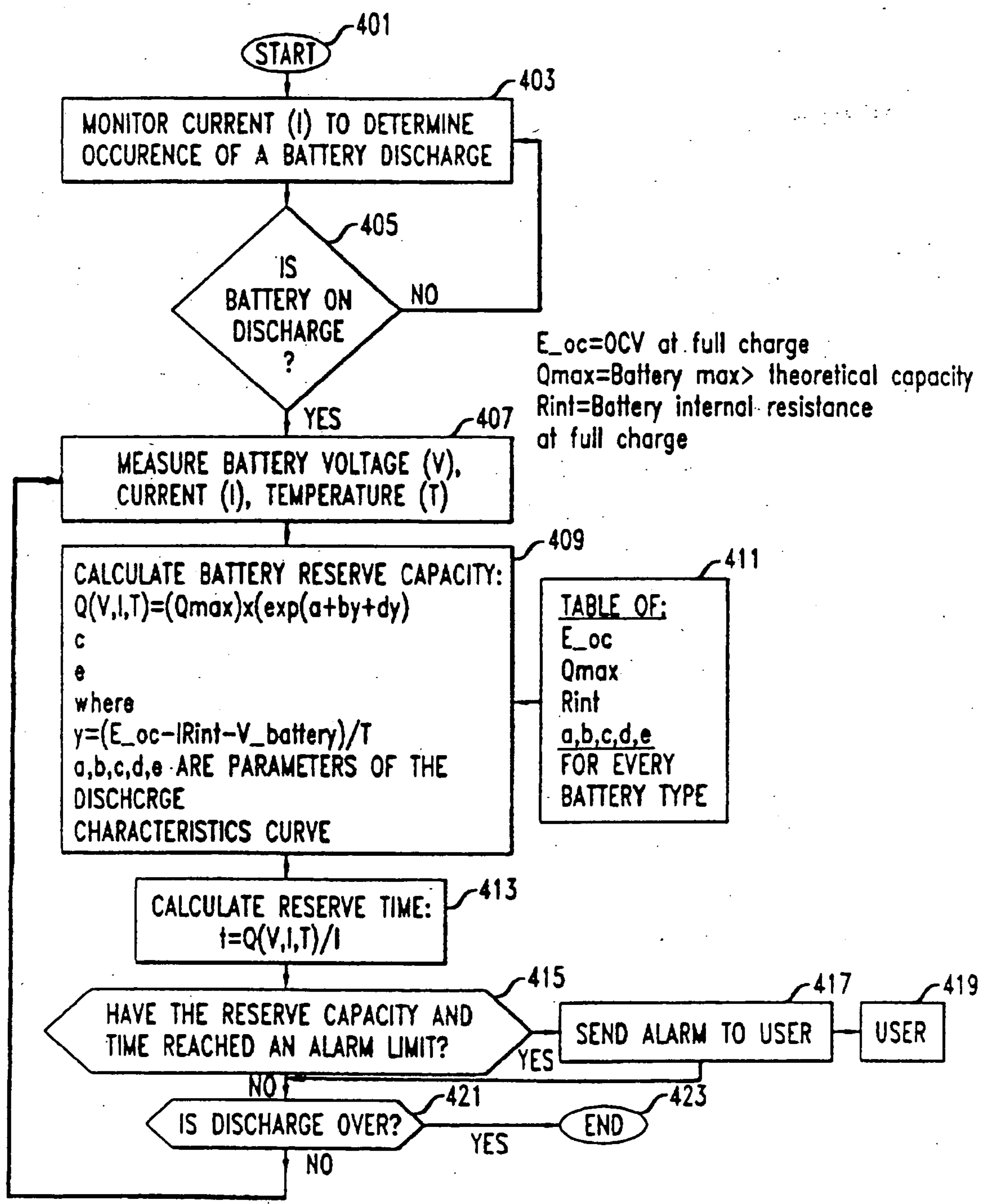

401
START
403
MONITOR CURRENT (I) TO DETERMINE OCCURENCE OF A BATTERY DISCHARGE
405
IS BATTERY ON DISCHARGE ?
NO
YES
E_oc=OCV at full charge
Qmax=Battery max> theoretical capacity
Rint=Battery internal resistance at full charge
407
MEASURE BATTERY VOLTAGE (V), CURRENT (I), TEMPERATURE (T)
409
CALCULATE BATTERY RESERVE CAPACITY:
Q(V,I,T)=(Qmax)x(exp(a+by+dy)
c
e
where
y=(E_oc-IRint-V_battery)/T
a,b,c,d,e ARE PARAMETERS OF THE DISCHCRGE CHARACTERISTICS CURVE
411
TABLE OF:
E_oc
Qmax
Rint
a,b,c,d,e
FOR EVERY BATTERY TYPE
413
CALCULATE RESERVE TIME:
t=Q(V,I,T)/I
415
HAVE THE RESERVE CAPACITY AND TIME REACHED AN ALARM LIMIT?
YES
417
SEND ALARM TO USER
419
USER
NO
421
IS DISCHARGE OVER?
YES
423
END
NO

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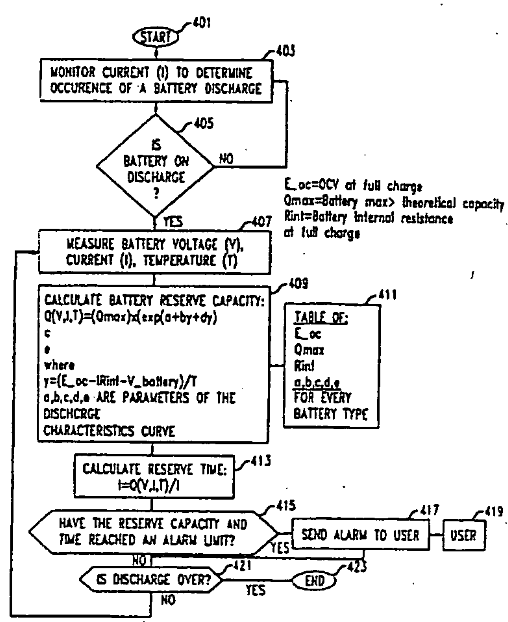
FIG. 4



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European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 95 30 8140

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	US-A-4 952 862 (BIAGETTI RICHARD V ET AL) 28 August 1990 * claim 1 * ---	1,11	G01R31/36
A	US-A-5 187 424 (BENZ KLEMENS ET AL) 16 February 1993 * claim 1 * ---	1,11	
A	DE-A-37 36 481 (GRASSLIN KG) 10 March 1988 * claim 1 * -----	1,11	
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)
			G01R

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	23 September 1996	Six, G

CATEGORY OF CITED DOCUMENTS

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E : earlier patent document, but published on, or after the filing date
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L : document cited for other reasons

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